Are We Seeing Magnetic Axis Reorientation in the Crab and Vela Pulsars?

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Received ______________; accepted ______________

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ABSTRACT

Variation in the angle α between a pulsar's rotational and magnetic axes would change the torque and spin-down rate. We show that *sudden* increases in α, coincident with glitches, could be responsible for the persistent increases in spin-down rate that follow glitches in the Crab pulsar. Moreover, changes in α at a rate similar to that inferred for the Crab pulsar account naturally for the very low braking index of the Vela pulsar. If α increases with time, all pulsar ages obtained from the conventional braking model are underestimates. Decoupling of the neutron star liquid interior from the external torque cannot account for Vela's low braking index. Variations in the Crab's pulse profile due to changes in α might be measurable.

Subject headings: dense matter — magnetic fields — stars: magnetic fields — stars: neutron — pulsars: individual (Crab, Vela)

1. Introduction

Although the rotational behavior of pulsars has been monitored in detail for decades, some aspects of how an isolated pulsar spins down are unresolved. Questions surround the manner in which angular momentum is removed from the system and how the different components of the neutron star interior couple to one another. In particular, most pulsars do not slow in a regular fashion, but undergo variations in their spin rates in the form of glitches and timing noise. Except for such timing irregularities, a pulsar is expected to slow down steadily. For example the *vacuum dipole model*, a theory of rotational energy loss to magnetic dipole radiation (Goldreich, Pacini, & Rees 1971), predicts $\dot{\Omega} \propto -\Omega^3$, where Ω is the pulsar rotational velocity. This spin-down law gives a braking index of $n_{\rm obs} \equiv \Omega\ddot{\Omega}/\dot{\Omega}^2 = 3$. Timing irregularities make meaningful determination of $\ddot{\Omega}$ and hence $n_{\rm obs}$ difficult or impossible in most cases. Consequently, the only braking indices available until recently were those for three very young, relatively quiet pulsars: the Crab pulsar ($n_{\rm obs} = 2.51 \pm 0.01$; Lyne, Pritchard, & Smith 1992), PSR B1509-58 ($n_{\rm obs} = 2.837 \pm 0.001$; Kaspi, *et al.* 1994), and PSR B0540-69 ($n_{\rm obs} = 2.24 \pm 0.04$; Boyd *et al.* 1995). These braking indices are in significant disagreement with the vacuum dipole model expectation. Plasma in the pulsar magnetosphere could carry angular momentum from the star and alter the magnetic structure from the dipolar configuration, giving a braking index as low as one (see, *e.g.*, Michel 1973). Another possibility is that the magnetic moment of the star changes in time, through either a change in the surface field strength (see, *e.g.*, Blandford, Applegate, & Hernquist 1983; Muslimov & Page 1995) or the angle between the magnetic and spin axes (see, *e.g.*, Beskin, Gurevich, & Istomin 1984; Link, Epstein, & Baym 1992; Pandey & Prasad 1996).

In the Crab pulsar, persistent increases in the spin-down rate are observed to accompany glitches (see, *e.g.*, Lyne, Pritchard, & Smith 1992 and Table 1). This phenomenon can in

principle be explained by either a sudden change in the external torque or in the moment of inertia acted upon by the torque. In this Letter we suggest that the persistent increases in the Crab's spin-down rate reflect sudden, glitch-induced reorientations of the star's magnetic axis that increase the external torque.

Recently, Lyne *et al.* (1996) attempted to separate the glitch activity of the Vela pulsar from its underlying spindown, and obtained a surprisingly small value of $\ddot{\Omega}$. If this small $\ddot{\Omega}$ reflects the true spin-down of the star, the braking index is only 1.4 ± 0.2. This braking index, far smaller than those for younger pulsars, suggests that the braking index decreases with time. This possibility forces reconsideration of traditional determinations of pulsar ages that assume constancy of the pulsar magnetic moment. In this Letter we demonstrate that shifts in α at a rate similar to that inferred for the Crab account naturally for Vela's low braking index.

2. The Crab Pulsar

The Crab pulsar has produced 6 glitches since 1969 (Lyne, Pritchard, & Smith 1992). During each glitch, the spin rate suddenly increases by $\Delta\Omega$ (see column 2 of Table 1). Immediately following each glitch, the magnitude of the spin-down rate $\dot{\Omega}$ is larger than before. Most of the excess spin-down rate decays within weeks of the glitch. However the long-term behavior, on which we focus here, shows a persistent shift (or *offset*) $\Delta\dot{\Omega}$ in the spin-down rate that does not decay (see column 3 of Table 1). This type of behavior was most striking after the 1989 glitch, in which the persistent shift in spin-down rate was especially large (see Fig. 1). Following the glitch, the spin-down rate remained larger than that expected from an extrapolation of the preglitch behavior. In all the glitches, the shifts in the spin-down rate persisted to the next glitch and were of the same sign. The cumulative effect of these offsets amounted to a total increase in the star's spin-down rate

of 0.07% over 23 years.

Any proposed mechanism for these persistent spin-down rate offsets must conserve angular momentum. The evolution of the angular velocity $\Omega(t)$ of a rigidly rotating pulsar under an external torque $N_{\rm ext}$, is

$$\frac{d(I\Omega)}{dt} = -N_{\rm ext}, \tag{1}$$

where I is the total moment of inertia. If the star contains a fluid component that is not coupled to the external torque, as discussed below, I is less than the star's total moment of inertia. A persistent shift in the spin-down rate could arise through an increase in the external torque (Gullahorn *et al.* 1977; Demiański & Prószyński 1983; Link, Epstein, & Baym 1992) or from a change in I (Baym & Pines 1971; Alpar & Pines 1993). The external torque could vary through either a change in the angle α between the spin and magnetic axes, or in the magnitude of the surface magnetic field, B. Gradual growth of the surface field has been considered (see, *e.g.*, Blandford, Applegate, & Hernquist 1983; Muslimov & Page 1995), however, no mechanism has been suggested by which the surface field could suddenly increase as a consequence of a glitch. Ruderman (1976) has suggested that stresses exerted on the inner crust by the superfluid crack the crust and move plates of material toward the equator. Because the magnetic field is frozen to the highly-conductive crust, such plate tectonics would increase α. Plate tectonic activity could also redistribute matter in such a way as to change the orientation of the principle axes of the star. As the star relaxes to a new rotational state, α can change, though the direction of change is not obvious.

We now discuss whether the Crab pulsar's behavior can be understood in terms of sudden changes in α. For illustration we use the vacuum dipole model, in which the rotational evolution is given by

$$\dot\Omega = -\frac{B^2R^6\sin^2\alpha}{6c^3I}\Omega^3. \tag{2}$$

If the alignment angle α changes by $\Delta\alpha$, the spin-down rate of the star shifts by an amount

$$\frac{\Delta\dot{\Omega}}{\dot{\Omega}} = \frac{2\Delta\alpha}{\tan\alpha}. \tag{3}$$

The average rate of change of $\Delta\dot{\Omega}/\dot{\Omega}$ due to glitches over 23 years of observations is (Lyne, Pritchard, & Smith 1992)

$$\frac{d}{dt}\langle\frac{\Delta\dot{\Omega}}{\dot{\Omega}}\rangle \simeq 3\times 10^{-5}\ \mathrm{yr}^{-1}. \tag{4}$$

To account for these persistent shifts, α must increase at an average rate of

$$\frac{\langle\dot{\alpha}\rangle}{\tan\alpha} \equiv \frac{1}{\tau_\alpha} = 1.5\times 10^{-5}\mathrm{rad\ yr}^{-1}. \tag{5}$$

The growth time τ_α is thus 7×10^4 yr. At this rate of change, the entire angular shift over the entire 10^3 yr lifetime of the star would be only $\sim t_{\rm age}/\tau_\alpha \sim 1/70$ rad, considerably less than the upper bound of $\pi/2$.

Another way for the star's spin-down rate to increase is through a decrease in the effective moment of inertia I on which the external torque acts. Such a change could occur through either a structural change of the star, *e.g.*, the star become less oblate, or through a decoupling of a portion of the star's liquid interior from the external torque. The change in the spin-down rate, from eq. [1] would be

$$\frac{\Delta\dot{\Omega}}{\dot{\Omega}} = -\frac{\Delta I}{I}. \tag{6}$$

A decrease in I solely through structural readjustment cannot produce the behavior seen in the Crab pulsar. In this case, angular momentum conservation would require the star to always spin *more* rapidly than had the glitch not occurred. The large persistent shifts following the 1975 and 1989 glitches, however, eventually caused the star to spin *less* rapidly than had the glitch not occurred (see Fig. 1). In principle, the Crab's spin-down rate offsets could be due to decoupling of a portion of the star's superfluid interior from the external torque (Alpar & Pines 1993; Alpar *et al.* 1996), though quantitative agreement of this model with the data has yet to be demonstrated.

3. The Vela Pulsar

The high levels of glitch activity and timing noise typically exhibited in older pulsars have prevented the determination of their braking indices. Recently, however, Lyne *et al.* (1996) attempted to separate the glitch activity of the Vela pulsar from its underlying spin-down to obtain the average $\ddot{\Omega}$. The inferred braking index is 1.4 ± 0.2, significantly smaller than the braking indices measured in the younger Crab, PSR B1509-58, and PSR B0540-69, suggesting evolution of $n_{\rm obs}$. Unlike the determinations of the braking indices in these young pulsars, which utilized data intervals that were free of glitches, the measurement of Vela's $n_{\rm obs}$ employed data containing many glitches. Hence, the value of Vela's $n_{\rm obs}$ includes the effects of any shifts in $\dot{\Omega}$ that might arise from glitches. Here we note that the small braking index for Vela reported by Lyne *et al.* (1996) could be due to increases in α of the sort suggested by the Crab's persistent shifts in spin-down rate.

Suppose that a pulsar spins down according to a braking law of the form

$$\dot{\Omega} = -K(t)\Omega^n, \tag{7}$$

where, for the vacuum dipole model, $K = B^2R^6\sin^2\alpha/6c^3I$ and $n = 3$. If K depends on time, the observed value of the braking index, $n_{\rm obs} \equiv \Omega\ddot{\Omega}/\dot{\Omega}^2$, will differ from n appearing in eq. [7]. If K is changing at an average rate $\dot{K}$, differentiating eq. [7] in time gives (see, *e.g.*, Michel 1991)

$$n - n_{\rm obs} = -\frac{\Omega\dot{K}}{\dot{\Omega}K} = 2t_{sd}\frac{\dot{K}}{K}\ , \tag{8}$$

where $t_{sd} \equiv \Omega/2|\dot{\Omega}|$, the conventional spin-down age, differs from the true age if K is evolving. Hence, if K is increasing with time, $n_{\rm obs}$ will be less than n. In the context of the vacuum dipole model, the growth rate of α required to explain the braking index of Vela is

$$\frac{\langle\dot{\alpha}\rangle}{\tan\alpha} \equiv \frac{1}{\tau_\alpha} = \frac{3 - n_{\rm obs}}{4t_{sd}} = 3.6 \times 10^{-5}{\rm rad\ yr}^{-1}, \tag{9}$$

giving a growth time $\tau_\alpha = 3 \times 10^4$ yr. This rate is remarkably close to the average rate of orientation shifts inferred from the persistent spin-rate shifts observed in the Crab (see eq. 5). The growth time is consistent with Vela's age, as $\tau_\alpha < t_{\rm age}$.

The changes in α at the average rate given in eq. [9] may occur suddenly, coincident with glitches, as we are suggesting for the Crab. Since the average glitch interval in Vela is ~ 3 yr, each glitch would then produce a persistent offset in the spin-down rate of $\Delta\dot{\Omega}/\dot{\Omega} \sim 2 \times 10^{-4}$, comparable to the shifts seen in the Crab. These persistent shifts would be very difficult to see in Vela; long after a glitch, $\dot{\Omega}$ typically differs from the average spin-down rate by $\sim 1\%$, much larger than the expected persistent shifts assuming the changes in α occur at glitches.

In principle, Vela's lower braking index could be due to a decreasing moment of inertia (Lyne *et al.* 1996). In this case, $\dot{K}/K = -\dot{I}/I$ in the vacuum dipole model, and the required rate of change is

$$-\frac{\dot{I}}{I} = \frac{3 - n_{\rm obs}}{2t_{sd}} \simeq \frac{0.8}{t_{sd}}. \tag{10}$$

If $n_{\rm obs}$ remains low over much of the star's life ($\gtrsim t_{sd}$), then the relative change in the moment of inertia would be of order unity (see also Michel 1991). Explanations based on either decoupling of the interior liquid or changes in the star's structure cannot accommodate such drastic decreases in I. In the standard picture of the neutron star interior, the only liquid component that can be decoupled is the inner crust neutron superfluid, which comprises at most 10% of the star's total moment of inertia. Furthermore, structural changes in I are limited by the deviation from sphericity due to rotation, which is $\Delta I/I \lesssim 10^{-4}$ for Vela.

4. Discussion

We have shown that the persistent offsets in the Crab's spin-down rate following glitches could be due to sudden glitch-induced increases in the angle α between the rotational and magnetic axes. Moreover, a similar average growth rate of α accounts for the very low braking index of the Vela pulsar. In the vacuum dipole model, the characteristic growth times of α in these two pulsars are $\tau_\alpha \sim 7 \times 10^4$ yr for the Crab and $\tau_\alpha \sim 3 \times 10^4$ yr for Vela.

Lyne and Manchester (1988) found that pulsars older than $\sim 10^6$ yr tend to have smaller α than younger pulsars. If our suggestion that α grows in young pulsars is correct, and the trend found by Lyne and Manchester (1988) is statistically significant, then the evolution of α is not monotonic. That is, in young pulsars ($t_{\rm age} \lesssim 10^4$ yr) the orientation angle α may grow, whereas in older pulsars it becomes smaller.

It is possible that changes in α are responsible for $n_{\rm obs} < 3$ for the Crab, PSR B1509-58, PSR B0540-69. Since the data intervals used to determine these braking indices contained no glitches, to explain these values of $n_{\rm obs}$ the alignment angle α would have to grow *between* glitches.

The changes in α inferred from the Crab's persistent offsets might produce measurable changes in the pulse profile. For example, a change of α at a glitch could change the duration of the line-of-sight's traverse through the pulse emission cone. The magnitude of the associated change in the total pulsed flux is $\sim |\Delta\alpha|/w_{1/2}$, where $w_{1/2}$ is the half-width of the emission cone. Taking $\alpha = 86^\circ$, determined from the radio data (Rankin 1990), $\Delta\alpha$ for the 1989 glitch (which exhibited the largest observed offset) is $\simeq 3 \times 10^{-3}$ rad (see eq. 3). From these numbers we estimate the relative change in pulsed flux to be $\sim 1\%$. We estimate a somewhat smaller change, $\sim 0.4\%$, using the value $\alpha = 80^\circ$ obtained by Yadigaroglu and Romani (1996) in their analysis of gamma ray and radio data. Such flux

changes may be measurable in either x-ray or optical bands. Sekimoto *et al.* (1995), using GINGA, found an upper limit on the change in the pulsed x-ray emission (1-6 keV) across the 1989 glitch of $< 1.6\%$. Moreover, Jones, Smith and Nelson (1980), found that the pulsed optical emission varied by $\sim 1\%$ over 7 yr.

We thank G. Baym for helpful comments on this manuscript, and A. G. Lyne for providing us with data from the 1989 Crab glitch. This work was performed under the auspices of the U.S. Department of Energy, and was supported in part by NASA EPSCoR Grant #291471, and by IGPP at LANL.

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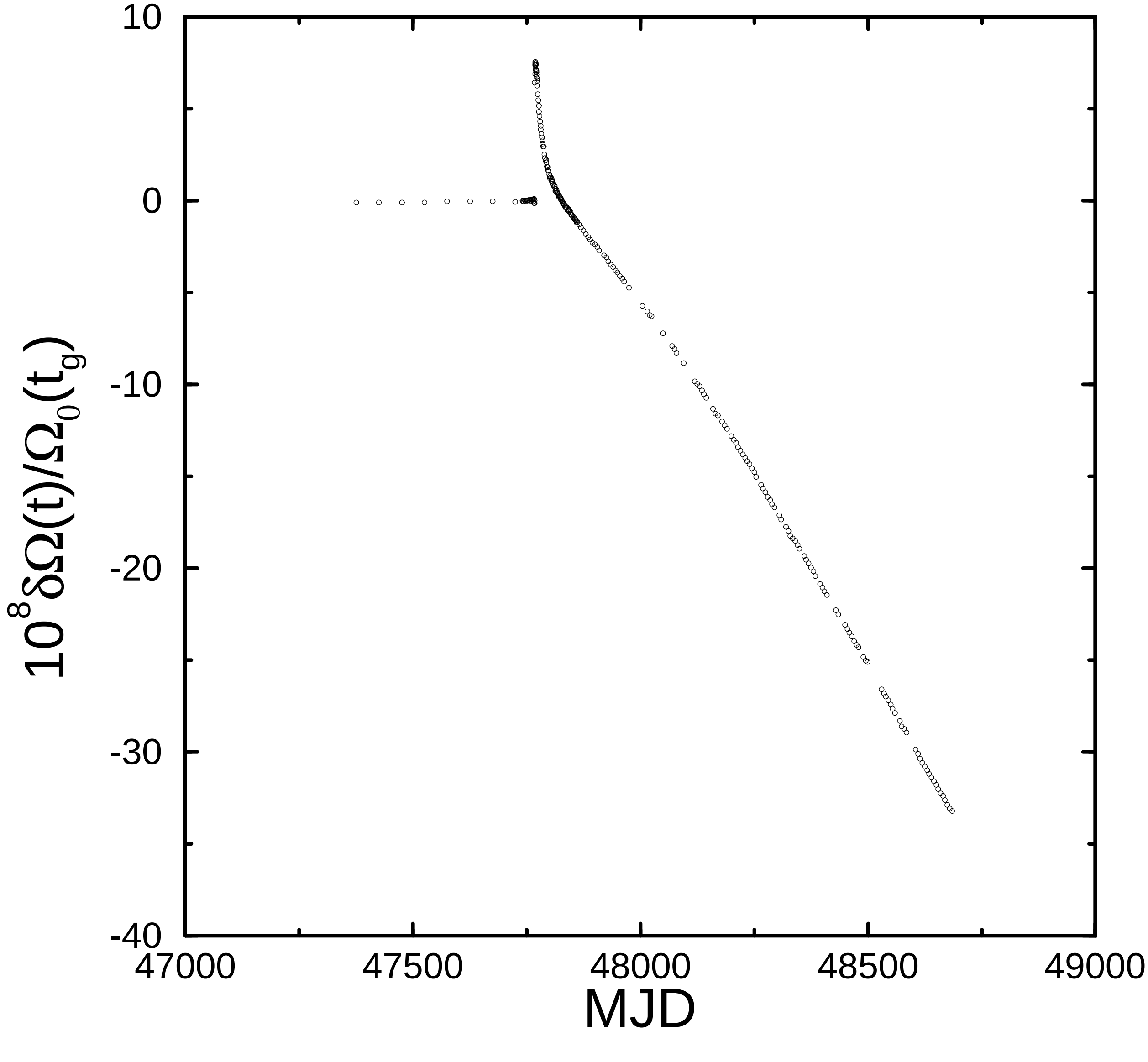
Fig. 1.— The behavior of the Crab pulsar surrounding the 1989 glitch at $t_g \simeq 47747$ MJD. The points show the difference $\delta\Omega(t) \equiv \Omega(t) - \Omega_0(t)$ between the observed spin rate and that expected from a model to the preglitch behavior $\Omega_0(t)$. A shift in the spin-down rate of $\Delta\dot{\Omega}/\dot{\Omega} \simeq 4 \times 10^{-4}$ persisted until the next glitch. By 40d after the glitch, the pulsar was spinning slower than had the glitch not occurred.

Table 1. Glitches of the Crab Pulsar[a]

Date	Glitch size $10^8\Delta\Omega/\Omega$	Persistent spin-down shift $10^4\Delta\dot{\Omega}/\dot{\Omega}$
1969 Sep	0.40	0.04
1975 Feb	4.4	2
1981	-	0.1
1986 Aug	0.41	0.2
1989 Aug	8.5	4
1992 Nov[b]	-	-

[a]From Lyne, Prichard, & Smith (1993).

[b]The behavior following the 1992 glitch is not yet published.



10
0
-10
-20
-30
-40
47000
47500
48000
48500
49000
MJD
$10^8\delta\Omega(t)/\Omega_0(t_g)$